DOT/FAA/AR-99/50

Office of Aviation Research
Washington, D.C. 20591

High-Intensity Radiated Fields (HIRF) Risk Analysis

July 1999

19991026 128

Final Report

U.S. Department of Transportation
Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/AR-99/50	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle HIGH-INTENSITY RADIATED FIELDS (HIRF) RISK ANALYSIS		5. Report Date July 1999 6. Performing Organization Code
7. Author(s) James R. Elliot		8. Performing Organization Report No.
9. Performing Organization Name and Address Electro Magnetic Applications, Inc. P.O. Box 260263 Denver, CO 80226-0263		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research Washington, DC 20591		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code AIR-130

15. Supplementary Notes

The Federal Aviation Administration William J. Hughes Technical Center COTR was Anthony Wilson.

16. Abstract

This report details the results of a study that has been completed to assess the risk of High-Intensity Radiated Fields (HIRF) to fixed-wing transport and nontransport aircraft in the U.S. The approach to the assessment of HIRF included the following elements:

- Detailed information on 893 emitters and 5913 flights near Denver and Seattle
- Quantitative judgements from industry experts about onboard avionics with regard to type, properties, and response probabilities.
- Electromagnetic environment levels from regulatory and standard sources DO-160B, DO-160C, and the proposed Notice of Proposed Rulemaking (NPRM).

Certification field strength levels from the proposed NPRM, DO-160B, and DO-160C were used to calculate the probability of a HIRF-induced catastrophic aircraft event. No clear evidence was found that flights in the Denver and Seattle areas experienced a HIRF environment level greater than the NPRM certification levels. The probability of the HIRF-induced catastrophic events are presented as a quantitative assessment of the HIRF risks to aircraft safety.

17. Key Words HIRF, Risk, Catastrophic, Analysis, Probability, Avionics, Fault	18. Distribution Statement This document is available to the public through the National Technical Information Service (NTIS) Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	25	

Form DOT F1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENTS

Dave Walen of the Federal Aviation Administration (FAA) and Richard Hess of Honeywell Flight Systems offered invaluable support and guidance during the course of this study. Don Nellis of the FAA also provided valuable information about the emitters. Rod Perala of EMA also offered important input to the study.

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EXECUTIVE SUMMARY

A study has been completed to assess the risk of High-Intensity Radiated Fields (HIRF) to fixed-wing transport and nontransport aircraft in the U.S. The approach to the assessment incorporated

- detailed information on 893 emitters and 5913 flights near Denver and Seattle;
- industry experience-based quantitative judgments about avionics on aircraft with regard to the types, properties, and response probabilities; and
- electromagnetic environment levels from regulatory and standards sources. The probability of a HIRF-induced catastrophic aircraft event was estimated for three different threat levels:

    1. DO-160B-derived field strengths corresponding to mid-1980s aircraft hardness levels,
    2. DO-160C-derived field strengths corresponding to "special condition" levels,
    3. Notice of Proposed Rulemaking (NPRM) field strengths corresponding to proposed certification levels.

No clear evidence was found for flights in the Denver or Seattle areas experiencing a HIRF environment greater than the NPRM certification levels. A worst case upper limit for a HIRF-induced catastrophic event for transport category aircraft from this study is set at ~2e-6; the actual probability might well be considerably lower for the NPRM certification environment. This worst case upper limit is at least 90 times lower than the probability estimated for the DO-160C associated levels and more than 15,000 times lower than the probability associated with the mid-1980s DO-160B levels. The upper limit for nontransport category aircraft cannot be set quite so low but is estimated to be ~1e-5 or lower. The nontransport category probabilities of a HIRF-induced catastrophic aircraft event associated with DO-160C and DO-160B are 3.5 and 2600 times larger, respectively.

INTRODUCTION

BACKGROUND.

Current Federal Aviation Administration (FAA) regulations require that aircraft systems and equipment operate as required in their intended environment. In recent years the advances and growth of radio communications and other electronic technologies have introduced into the operational environment a phenomena know as High-Intensity Radiated Fields (HIRF). There are more than 500,000 emitters in the U.S. and Western Europe contributing to the electromagnetic environment. Aircraft are exposed to the HIRF environments that emanate from high-powered radio and television frequency transmitters, radar and satellite uplink transmitters, and large microwave communications systems. Electrical and electronic systems are fast replacing mechanical devices to perform functions in aircraft flight and navigation systems that are necessary for the continued safe flight and landing of the aircraft. Basic functions such as engines and flight controls may be inoperative without their electronic control systems. Research indicates that aircraft electrical and electronic systems that perform critical functions may not be able to withstand the electromagnetic fields generated by HIRF and could become inoperable. Despite the fact that no transport category aircraft accident attributed to HIRF has occurred, the susceptibility of aircraft electrical and electronic systems to malfunction or failure when exposed to HIRF presents a threat to aviation safety systems. Therefore, it is desirable to have quantitative assessment of the risks to aircraft safety from HIRF.

GOALS.

An approach was developed and implemented to perform the assessment of HIRF-induced risk to fixed-wing aircraft associated with HIRF. Key elements of the approach were

- identification of the components of a HIRF interaction,
- quantitative estimation of the probabilities associated with these interaction components, and
- evaluation of the consequences and overall occurrence probabilities.

SCOPE AND INPUTS.

The philosophy for this HIRF risk evaluation was to build on results from previous HIRF committees and research contracts as well as avionics manufacturing experience. These include

- maximum field strengths encountered by aircraft in the U.S.;
- strengths, locations, and other characteristics of emitters in the Denver and Seattle areas;
- emitter-aircraft separation for various types of aircraft and for various phases of flight operation;
- actual flight paths for periods of three days in both the Denver and Seattle areas;

- industry knowledge of the response of avionics exposed to various levels of electromagnetic fields; and
- past and present equipment and aircraft qualification levels.

FAULT ANALYSIS AND CONSTITUENT PROBABILITIES

OVERVIEW.

There are three major factors in an aviation HIRF event: (1) an aircraft in flight, (2) an active emitter, and (3) onboard avionics performing functions necessary for safe flight. Upon further analysis, each of these items can be resolved into components which have their own complicated dependencies and probabilities of occurrence. Figure 1 illustrates a fault analysis with one possible identification of components. All of the boxes represent conditions required for the occurrence of a HIRF-aircraft interaction with catastrophic consequences and are grouped according to the three major factors listed above.

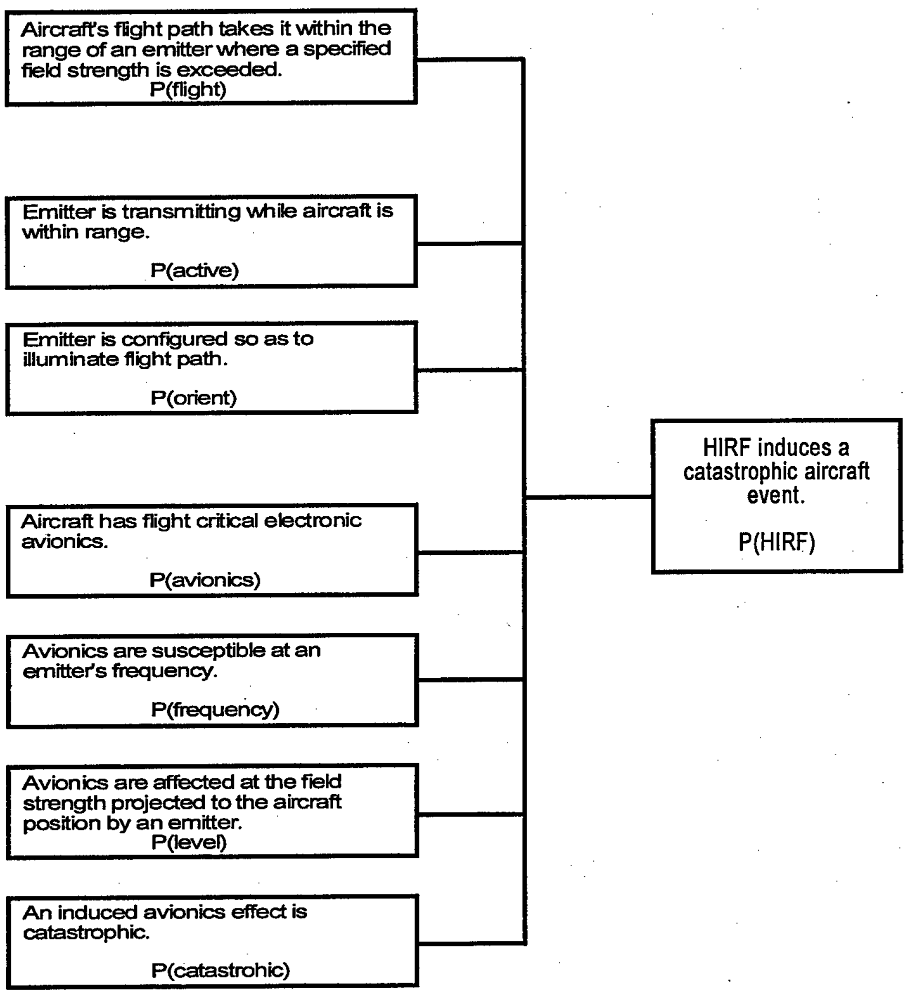

FIGURE 1. FAULT CONDITIONS REQUIRED FOR A HIRF-INDUCED CATASTROPHIC EVENT

Note that, strictly speaking, this fault analysis is valid for a particular aircraft on a particular flight path in a particular location at a particular time of day and year. There are implicit correlations between some of the components which means that truly independent probabilities do not exist for the components. For example, the probability of avionics susceptibility depends on the frequency of the emitter but this depends on which emitter is being considered, which, in turn, depends on the flight path. For this reason, a more legitimate approach is to calculate the entire probability chain for an actual flight with an actual set of emitters. If a representative set of flights is available, the overall probability can be obtained by taking the average over the set of flights.

Each of the components will be discussed in turn and estimates presented for the associated probabilities. Table 1 summarizes the information on each of these components. The two features unique to this risk study are (1) the use of actual flight path positions as obtained from radar recordings in the Denver and Seattle areas and (2) the use of information on all the relevant emitters in the Denver and Seattle areas. Because of their importance, specific flight paths, specific emitters, and their correlation will be dealt with more fully in a later section.

TABLE 1. FAULT COMPONENT SUMMARY

Fault Component	Component Probability Value	Component Value Sources
P(flight)	Varied, refer to: - Section on "Aircraft, Emitters, and Correlations" - Table 11	• Government databases for emitters • FAA recordings of aircraft positions during flight • Electromagnetic levels from standards groups • EMA analysis
P(active)	1	• Estimate from industry experience
P(orient)	1 $(2\pi / d\Omega)$	• Assumed worst case • Unless known to operate with single-fixed antenna beam and direction
P(avionics)	1	• Assumed worst case • May be adjusted for a fleet with known aircraft composition
P(frequency)	• Refer to table 3	• Estimate from industry experience
P(level)	• Refer to figures 2 and 3	• Estimate from industry experience
P(catastrophic)	0.1	• Estimate from industry experience

<u>P(flight)</u>.

This is the probability that, during flight, an aircraft is exposed to HIRF at or above some specified level. As stated above, this depends on flight path and emitter information which will be detailed in Aircraft, Emitters, and Correlations.

It is convenient to specify the field strength levels for each of a set of frequency intervals. The frequency intervals chosen are the same as those commonly used in previous efforts to characterize the HIRF environment. These frequency intervals are shown in table 2. For this risk assessment, three different sets of comparison levels are used; they are all listed in table 2. Note that values are included for both average and peak field strengths.

NPRM CERTIFICATION LEVELS. The FAA has proposed making a rule for HIRF standards for aircraft and electrical and electronic systems. The notices of proposed rulemaking includes HIRF environments defined by field strength. For transport aircraft (FAR part 25) and for normal, utility, acrobatic, and commuter aircraft (FAR part 23), the field strengths are included in table 2 [1].

TABLE 2. FIELD STRENGTHS USED FOR COMPARISONS WITH LEVELS CALCULATED AT AIRCRAFT POSITIONS

	NPRM Certification Field Strength [V/m]		DO-160B-Derived Field Strength [V/m]		DO-160C-Derived Field Strength [V/m]	
Frequency	Average	Peak	Average	Peak	Average	Peak
10 - 100 kHz	50	50	3	3	300	300
100 - 500 kHz	50	50	3	3	300	300
500 kHz - 2 MHz	50	50	3	3	300	300
2 - 30 MHz	100	100	3	3	300	300
30 - 70 MHz	50	50	3	3	300	300
70 - 100 MHz	50	50	3	3	300	300
100 - 200 MHz	100	100	3	3	300	300
200 - 400 MHz	100	100	3	3	300	300
400 - 700 MHz	50	700	3	3	300	300
700 MHz - 1 GHz	100	700	3	3	300	300
1 - 2 GHz	200	2000	3	3	300	300
2 - 4 GHz	200	3000	3	3	300	300
4 - 6 GHz	200	3000	3	3	300	300
6 - 8 GHz	200	1000	3	3	300	300
8 - 12 GHz	300	3000	3	3	300	300
12 - 18 GHz	200	2000	3	3	300	300
18 - 40 GHz	200	600	3	3	300	300

DO-160B-DERIVED LEVELS. In 1984, there were no HIRF standards for onboard avionics. However, there were radiated and conducted susceptibility tests and levels specified in reference 2. These were not aircraft levels but system and subsystem bench test average levels which did not exceed 1 V/m and were specified only up to 1.2 GHz. In order to assess the HIRF risk of aircraft manufactured in this era and compare it in a uniform way to aircraft manufactured to withstand proposed HIRF standard levels, it is necessary to convert the DO-160B levels to field strengths illuminating aircraft exteriors and to extend the frequency range. This conversion and extension is shown in table 2. In the absence of detailed information, a uniform exterior

level of 3 V/m up to 40 GHz is chosen for both average and peak field strengths. This was guided by avionics and aircraft industry experience and was arrived at during a discussion with Richard Hess of Honeywell Flight Systems and Dave Walen of the FAA, both of whom act as resources for electromagnetic effects on aircraft.

DO-160C-DERIVED LEVELS. Later, as the FAA and others became aware of the potential hazards of HIRF, special conditions were established and standards revisions led to DO-160C [3]. This document also specified bench test procedures and levels but extended the frequency range to 18 GHz and established hardness levels of 200 V/m for the most exposed systems and components. Using the same exterior to interior coupling considerations that were used for DO-160B results in exterior levels of 300 V/m for both average and peak field strengths up to 40 GHz. These are recorded in table 2.

P(active).

This is the probability that an emitter is actually powered up and functioning while the aircraft is potentially within the required range. Some emitters, such as AM, FM, and TV broadcast stations, are not on the air 24 hours each day and may not be transmitting during a particular flight. This may also be true for other emitters such as experimental emitters with only occasional use. However, many other emitters are operated continuously, or nearly so. Examples of these would be radars for airport and air route surveillance as well as some ground and satellite communications transmitters. Unfortunately, there is no database which provides this information in a comprehensive and reliable way. Therefore P(active) = 1 is assumed. This is a pessimistic worst case but many of the emitters of most concern, such as radars, do operate nearly continuously.

P(orient).

This is the probability that a transmitter is actually configured so that any significant amount of its power is emitted in the particular direction of an aircraft in flight. This would mostly be for emitters with fixed beams or limited antenna scans. For example, an air route surveillance radar scans 360 degrees several times per minute and would be assumed to be able to illuminate an aircraft in any direction, therefore P(orient) = 1 (the field strength variation due to antenna pattern is treated separately and discussed in the section on flight paths and emitters). On the other hand, a satellite communications uplink, which has a beam covering $d\Omega$ and has P(orient) = $2\pi / d\Omega$; this assumes no correlation between the satellite direction and an aircraft flight path. Actually, the two may be constrained to a region less than the full 2π, but this constraint is not expected to have a strong effect on the probability.

P(avionics).

This is the probability that an aircraft has avionics that are flight critical. Calculation of this probability value includes knowing the date of manufacture of the aircraft, its size, and type. For an entire fleet, this probability will depend on the particular mix of aircraft at the time of consideration. P(avionics) = 1 is used in this study, but overall results may be rescaled if the fleet under consideration is known to have a different value for P(avionics).

P(frequency).

This is the probability that, for a particular frequency of HIRF, the avionics has the potential for susceptibility. This reflects the fact that avionics are not completely wideband but have limited operating frequencies of their own and an emitter frequency might not coincide with any of the operating frequencies. The probabilities themselves vary with frequency, and it is convenient to organize them according to the same frequency, intervals which were used before for HIRF levels. The values, shown in table 3, are based on avionics and aircraft industry experience and were arrived at during a discussion with Richard Hess of Honeywell Flight Systems and Dave Walen of the FAA.

TABLE 3. ESTIMATED PROBABILITY THAT AN EMITTER TRANSMITS AT A FREQUENCY AT WHICH AN AIRCRAFT IS SUSCEPTIBLE

	Probability	
Frequency	Average Field Strength	Peak Field Strength
500 kHz - 2 MHz	0.2	0.2
2 - 30 MHz	0.5	0.5
30 - 70 MHz	0.5	0.5
70 - 100 MHz	0.5	0.5
100 - 200 MHz	0.3	0.3
200 - 400 MHz	0.1	0.2
400 - 700 MHz	0.1	0.2
700 MHz - 1 GHz	0.1	0.2
1 - 2 GHz	0.1	0.2
2 - 4 GHz	0.05	0.05
4 - 6 GHz	0.05	0.05
6 - 8 GHz	0.05	0.05
8 - 12 GHz	0.05	0.05
12 - 18 GHz	0.05	0.05
18 - 40 GHz	0.05	0.05

P(level).

This is the probability that the HIRF field strength is sufficient to have some kind of affect, not necessarily serious, upon the operation of an aircraft's avionics. It is assumed that, while a threshold may exist, affects will be seen ever increasingly as field strengths grow larger than the threshold. The probability of affect as a function of electric field strength (normalized to the threshold value) is shown in figures 2 and 3. Figure 2 is used when the threshold value is relatively low, as might have been appropriate to systems qualified in the past to DO-160B levels and having more response variation. Figure 3 is used when the threshold value is relatively high corresponding to DO-160C or the levels associated with the current FAA NPRM.

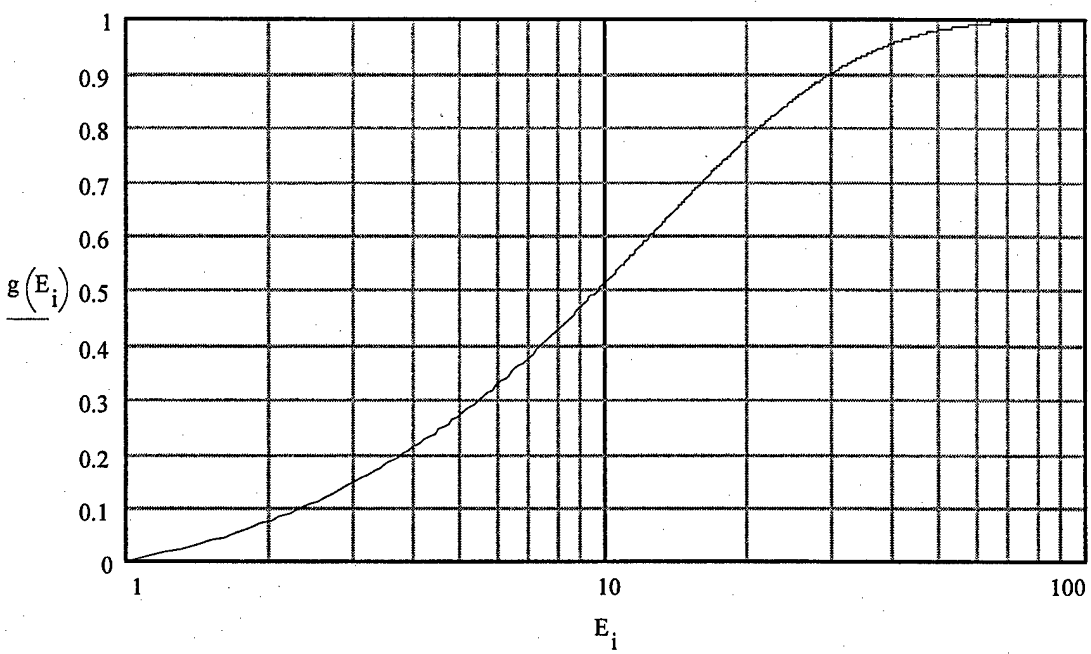

FIGURE 2. ESTIMATED PROBABILITY OF SUSCEPTIBILITY, P(level), AS A FUNCTION OF ELECTRIC FIELD NORMALIZED TO NOMINAL HARDNESS LEVELS DERIVED FROM DO-160B

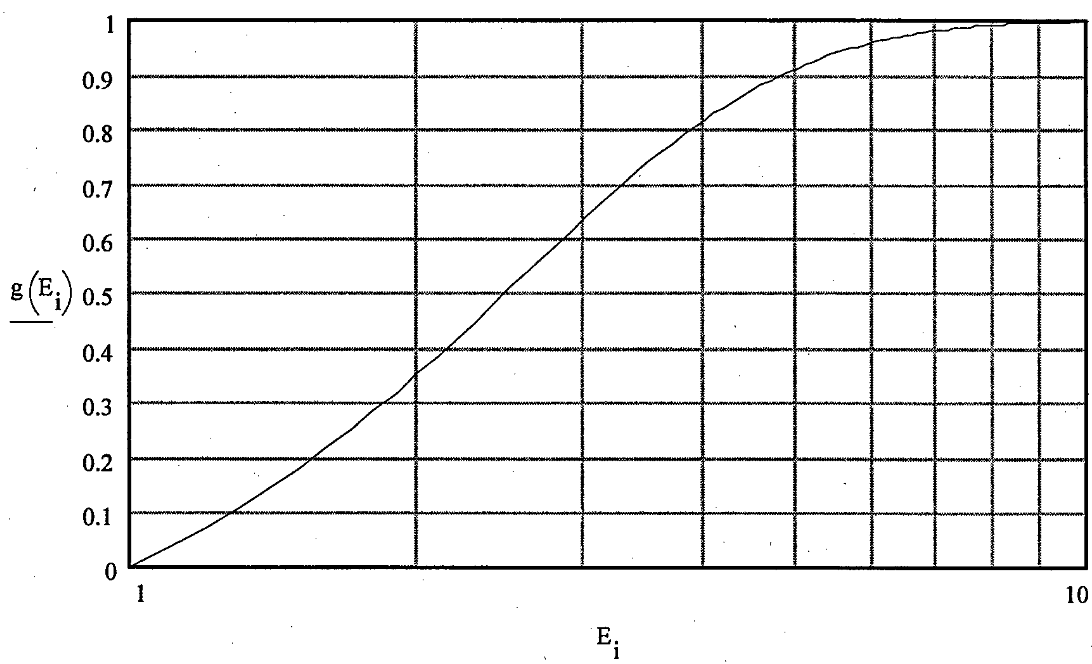

FIGURE 3. ESTIMATED PROBABILITY OF SUSCEPTIBILITY, P(level), AS A FUNCTION OF ELECTRIC FIELD NORMALIZED TO NOMINAL HARDNESS LEVELS DERIVED FROM DO-160C AND NPRM CERTIFICATION REQUIREMENTS

P(catastrophic).

This is the probability that, when HIRF affects avionics performing functions critical to flight safety, the result will be catastrophic. A uniform P(catastrophic) = 0.1 is used. This estimate is based on avionics and aircraft industry experience and was arrived at during a discussion with Richard Hess of Honeywell Flight Systems and Dave Walen of the FAA.

AIRCRAFT, EMITTERS, AND CORRELATIONS

AIRCRAFT FLIGHT PATHS.

In a previous study of the distance of closest approach of aircraft to ground-based emitters [5-7], FAA system analysis record (SAR) tapes were accessed to obtain flight identification and position information. The data collected covered three days each in both the Denver and Seattle areas. Various processing techniques were used to eliminate or correct data deficiencies in order to arrive at a set of flight paths associated with aircraft either operating in/out of the area airports or passing through the area. Details of the processing are available in references 5-7.

By separating flights with beacon codes of 1200 and known local usage codes from the others, it was possible to split the flights into two categories, one composed mostly of transport type aircraft and the other composed of mostly normal, utility, and commuter type aircraft. Table 4 summarizes the number of flight paths obtained. For Denver the extraction of flights of the nontransport category was only partially successful and no such Denver flights are used in this study.

For risk assessment, it was desirable to make a few clarifying assumptions. Since the flight path data was limited to aircraft positions within approximately 75 miles of either Denver or Seattle, at best, only a takeoff or landing phase or possibly a section of the en route phase of a transport category flight was captured. For many reasons, during the en route phase of a flight, an aircraft is inherently at a much lower risk due to HIRF than during the takeoff or landing phases. Therefore, the risk accumulated during the takeoff and landing phases will dominate the probability of an adverse HIRF interaction. For this reason, the flight paths used in this analysis were required to initiate or end at an area airport. Since the available data did not always cover the flight down to ground level, some conservative extrapolation to the runway was required, particularly for the Seattle area. (Table 11 shows the final number of flights used in the risk assessment.) A flight path with only a takeoff or a landing was regarded as representing only one-half of the flight's total risk while a path with both a takeoff and a landing was regarded as representing a flight's total risk.

TABLE 4. NUMBER OF FLIGHT PATHS AVAILABLE

	Denver Transport	Seattle Transport	Seattle Nontransport
All Flights	~5100	~5300	~2250
Flights with local termination	~3150	~1750	~1000

EMITTERS.

The previous studies [5-7] cited obtained information from the Government Master File (GMF) but used only emitters with frequencies > 400 MHz. For this risk assessment, it was desirable to cover the entire HIRF frequency spectrum. For this reason, all GMF emitters were considered and AM, shortwave, FM, and television broadcast stations were identified using Federal Communications Commission (FCC) databases. The emitter information from these databases was extracted and put into the same format as the earlier acquired GMF information. Similar to previous work with the GMF emitters, some processing was required to provide estimates for missing parameters. Mainly, this involved site elevation, antenna height, and antenna gain. Table 5 lists the number of emitters in the Denver and Seattle areas in each of the frequency intervals commonly used in HIRF characterization. AM, FM, and TV stations are assumed to have a duty factor equal to 1 so their peak and average field strengths will be identical. However, GMF emitter information included duty factor which allowed separate calculation of average and peak field strengths.

Unfortunately, neither the GMF nor the FCC information was totally reliable. Therefore, during a final pass through the emitter data, in each frequency interval, the nominal field strength at a chosen distance (100 ft) was not allowed to exceed the values, average, and peak determined in a survey of maximum strength emitters located within the U.S.[4].

TABLE 5. NUMBER OF EMITTERS IN EACH FREQUENCY BAND IN DENVER AND SEATTLE

	Number of Emitters	
Frequency	Denver	Seattle
500 kHz - 2 MHz	37	70
2 - 30 MHz	1	5
30 - 70 MHz	6	3
70 - 100 MHz	19	23
100 - 200 MHz	19	15
200 - 400 MHz	4	9
400 - 700 MHz	12	16
700 MHz - 1 GHz	48	32
1 - 2 GHz	31	25
2 - 4 GHz	20	44
4 - 6 GHz	20	84
6 - 8 GHz	11	51
8 - 12 GHz	29	89
12 - 18 GHz	29	74
18 - 40 GHz	19	48

CORRELATIONS.

Given an aircraft's position and an emitter's location, it is straightforward to calculate the separation distance between the two. This was the thrust of the previous studies using the same aircraft position and emitter information used in the present risk assessment. The NPRM's for HIRF include various minimum distances between aircraft and emitters, depending on details of the emitters, aircraft, and the locations involved. These distances were used with the maximum strength U.S. and Western European emitters to define the certification HIRF environment in the NPRM's. Table 6 summarizes these distances as implemented in this risk assessment.

TABLE 6. MINIMUM DISTANCE FROM EMITTER TO AIRCRAFT USED IN CALCULATION OF FIELD STRENGTHS

Emitter Location	Distance
Inside airport runway boundaries, non-ASR/ARSR emitters	250 ft, slant range
Inside airport runway boundaries, ASR/ARSR emitters	500 ft, slant range
Outside airport runway boundaries but within 3 miles	500 ft, slant range
Outside airport runway boundaries by more than 3 miles	Calculated slant range for aircraft height at least 1000 ft above ground (and 1000 ft above the given emitter if within 1 mile)

Starting with a separation distance corresponding to a specific emitter and a specific aircraft position, an inverse distance relationship is used to transform the nominal maximum field strength for an emitter to the field strength at the specific aircraft position. For antennas with nonuniform field patterns, it is necessary to modify the maximum field value by the angular dependent gain factor. In this study, such a dependence was implemented for three types of emitters:

- AM broadcast: vertical dipole over a ground plane
- FM and TV broadcast: cosine**2 dependence on elevation angle
- Scanning radar: cosecant dependence on elevation angle up to a maximum angle.

For a given emitter, once the exterior aircraft field strength at a specific position is calculated, it is compared to the nominal hardness level at the emitter's frequency (see table 2). For a flight, as long as the calculated field value is less than the nominal hardness level, nothing more is required. However, if the nominal hardness level is exceeded, a HIRF hazard exists and the other probabilities enumerated in the fault analysis are computed using the maximum external aircraft field associated with the given emitter. A similar procedure is followed for all emitters in the area and the probabilities associated with all of them act as input to the probability of the flight having a HIRF-induced catastrophic aircraft event. As would be expected, susceptibility to multiple emitters increases the probability P(HIRF) for a flight.

PROBABILITY RESULTS

TRANSPORT AIRCRAFT.

Using the flight, emitter, and correlation information just discussed and the probabilities associated with the fault analysis (tables 1 and 2), expectation values can be obtained for a HIRF-induced catastrophic aircraft event. For transport category aircraft, these estimates can be made separately for Denver and Seattle. It is also possible to isolate the probability contributions from emitters below and above 1 GHz and for average and peak field strengths. Tables 7 and 8 (top line in each box) summarize these results for transport aircraft.

Imposing the minimum separation distance requirement and the maximum field strength requirement described above, no flight can exceed the NPRM levels. However, if the minimum separation distance requirement is not imposed, the italicized values (lower line in each box) in tables 7 and 8 result. Table 11 reveals that two flights in Denver had separation distances (ranging from ~ 50-100 ft) less than those limits specified in the NPRM. This can be due either to errors in the Denver aircraft/emitter information (including radar resolution which is typically 165-330 ft) or to real flight paths occurring very close to emitters. From the information available, it is impossible to say definitely but an information error is more likely. The accumulated time above the reference level is 141 seconds for the flight exceeding the allowed average level and 9 seconds for the flight exceeding the allowed peak level. Even assuming the worst, the chance of the HIRF certification field levels being exceeded is, at most, on the order of one in a million.

Imposing the minimum separation distance requirements again, the still relatively high hardness levels derived from DO-160C, the average field strengths have no problems either below or above 1 GHz. However, the peak levels above 1 GHz derived from DO-160C exceeded by 17 flights in the Denver sample and by 280 flights in the Seattle sample (table 11). When the other probability factors are included, expectation values for the HIRF risks for the two cities range from 0.2e-4 to 5.e-4. Upon closer examination of the Dopler, it was found that four emitters, all of which were weather or Air Surveillance Radars, were primarily responsible for the probabilities associated with field strength. There are also four emitters responsible in Seattle, three radars and a satellite uplink transmitter. In Denver, a single emitter generates the offending field strengths for approximately 67% of these flights and the average time above the reference level is less than 50 seconds for all 17 flights. Likewise, in Seattle a single emitter is responsible for over 90% of the flights having the offending fields strengths and the average time above the reference level is less than 5 seconds. Removing the NPRM minimum separation distance does not significantly affect the probabilities associated with the DO-160C-derived field strengths.

By contrast, the much lower levels associated with the older DO-160B are exceeded for both average and peak field strengths both below and above 1 GHz in both Denver and Seattle. Moreover, the levels are exceeded on every flight by many emitters (18 to 24 on average), including television stations. The probability range is 3.e-2 to 4.e-2 for Denver and Seattle. Removing the NPRM minimum separation distance does not significantly affect the probabilities associated with the DO-160B-derived field strengths.

TABLE 7. ESTIMATES OF CATASTROPHIC HIRF EVENT PROBABILITIES BASED ON TRANSPORT AIRCRAFT TRAFFIC NEAR DENVER (Italicized values do not have minimum separation distance imposed.)

Comparison Level	Average Field			Peak Field			Peak/Average Field		
	Frequency < 1 GHz	Frequency > 1 GHz	All Frequencies	Frequency < 1 GHz	Frequency > 1 GHz	All Frequencies	Frequency < 1 GHz	Frequency >1 GHz	All Frequencies
DO-160B	1.3e-3 *1.6e-3*	1.6e-5 *2.1e-5*	1.4e-3 *1.6e-3*	7.9e-4 *1.0e-3*	2.8e-2 *2.8e-2*	2.9e-2 *2.9e-2*	2.1e-3 *2.6e-3*	2.8e-2 *2.8e-2*	3.0e-2 *3.1e-2*
DO-160C	0 *0*	0 *0*	0 *0*	0 *0*	2.5e-5 *3.5e-5*	2.5e-5 *3.5e-5*	0 *0*	2.5e-5 *3.5e-5*	2.5e-5 *3.5e-5*
Certification	0 *2.6e-6*	0 *0*	0 *2.6e-6*	0 *0*	0 *5.6e-7*	0 *5.6e-7*	0 *2.6e-6*	0 *5.6e-7*	0 *3.1e-6*

TABLE 8. ESTIMATES OF CATASTROPHIC HIRF EVENT PROBABILITIES BASED ON TRANSPORT AIRCRAFT TRAFFIC NEAR SEATTLE (Italicized values do not have minimum separation distance imposed.)

Comparison Level	Average Field			Peak Field			Peak/Average Field		
	Frequency < 1 GHz	Frequency > 1 GHz	All Frequencies	Frequency < 1 GHz	Frequency > 1 GHz	All Frequencies	Frequency < 1 GHz	Frequency > 1 GHz	All Frequencies
DO-160B	1.2e-3 *1.2e-3*	1.7e-3 *1.7e-3*	2.9e-3 *2.9e03*	6.9e-4 *7.9e-4*	3.9e-2 *3.9e-2*	4.0e-2 *4.0e-2*	1.8e-3 *2.0e-3*	4.1e-2 *4.1e-2*	4.3e-2 *4.2e-2*
DO-160C	0 *0*	0 *0*	0 *0*	0 *0*	4.5e-4 *4.5e-4*	4.5e-4 *4.5e-4*	0 *0*	4.5e-4 *4.5e-3*	4.5e-4 *4.5e-4*
Certification	0 *0*	0 *0*	0 *0*	0 *0*	0 *0*	0 *0*	0 *0*	0 *0*	0 *0*

Table 9 give the expectation values of the probabilities of HIRF-induced catastrophic aircraft events when the Denver and Seattle data are combined.

NONTRANSPORT AIRCRAFT.

Table 10 shows the probability results for nontransport aircraft near Seattle. The probability expectation values for the nontransport category Seattle flights are usually within a factor of two of the overall values for the transport category Seattle flights, although the average time above the reference field levels is nearly four times greater. Removing the NPRM minimum separation distance does not significantly affect the probabilities associated with the DO-160B/C-derived field strengths for nontransport aircraft near Seattle.

INFERENCES

TRANSPORT AIRCRAFT.

The nearly 5000 sampled flights in the Denver and Seattle areas never experience fields in excess of the NPRM HIRF certification environment. When the minimum distance assumptions of the NPRM are removed, only a handful of flights (two transport category in the Denver area) were observed to exceed the certification level. Discounting this small number of exceptions as spurious, due to inaccuracies in recording aircraft positions, there was no evidence that the NPRM certification levels were exceeded for transport category flights in the Denver and Seattle areas. This would make it appear that the minimum distance assumptions of the NPRM are validated. On the other hand, working in a worst case mode, the exceptions can be used to set an upper limit for a HIRF catastrophic event, ~2.e-6. The probability associated with the HIRF environment derived from DO-160C is ~1.8e-4, which is 90 times larger than the NPRM worst case upper limit. This would indicate that the NPRM certification levels are effective in achieving an additional flight safety as compared to the "special conditions" or DO-160C-derived levels. Comparison of the worst case upper limit probability for NPRM certification levels to the probability for the mid-1980s DO-160B-derived levels indicates a reduction of more than a factor of 15,000 in the probability of a HIRF-induced catastrophic aircraft event. These conclusions should be useful to the extent that the Denver and Seattle areas are representative of other flight and emitter conditions in the U.S.

NONTRANSPORT AIRCRAFT.

The nontransport aircraft category has only the approximately 1000 flights in the Seattle area to draw upon. There are a handful of flights (four) with emitter-aircraft separation distances less than those used in the NPRM. As for the transport category aircraft in Denver, it is likely that these are spurious introduced by limited radar resolution or other data errors and there is no real evidence of aircraft encountering electromagnetic field levels in excess of the NPRM certification levels. However, using these flights in a worst case fashion, one obtains an upper limit of ~7.2e-5 probability of a HIRF-induced catastrophic aircraft event for the NPRM certification levels. The DO-160C associated probability is a factor of two smaller and based on an order of magnitude more flights. The DO-160B-derived levels have a probability more than 300 times higher. More reasonably, the NPRM associated upper limit is likely to be closer to the

TABLE 9. ESTIMATES OF CATASTROPHIC HIRF EVENT PROBABILITIES BASED ON TRANSPORT AIRCRAFT TRAFFIC NEAR DENVER AND SEATTLE (Italicized values do not have minimum separation distance imposed.)

Comparison Level	Average Field			Peak Field			Peak/Average Field		
	Frequency < 1 GHz	Frequency > 1 GHz	All Frequencies	Frequency < 1 GHz	Frequency > 1 GHz	All Frequencies	Frequency < 1 GHz	Frequency >1 GHz	All Frequencies
DO-160B	1.3e-3 *1.4e-3*	6.3e-4 *6.3e-4*	1.9e-3 *2.1e-3*	7.6e-4 *9.2e-4*	3.2e-2 *3.2e-2*	3.3e-2 *3.3e-2*	2.0e-3 *2.4e-3*	3.3e-2 *3.5e-2*	3.4e-2 *3.5e-2*
DO-160C	0 *0*	0 *0*	0 *0*	0 *0*	1.8e-4 *1.8e-4*	1.8e-4 *1.8e-4*	0 *0*	1.8e-4 *1.8e-4*	1.8e-4 *1.8e-4*
Certification	0 *1.7e-6*	0 *0*	0 *1.7e-6*	0 *0*	0 *3.6e-7*	0 *3.6e-7*	0 *1.7e-6*	0 *3.6e-7*	0 *2.0e-6*

TABLE 10. ESTIMATES OF CATASTROPHIC HIRF EVENT PROBABILITIES BASED ON NONTRANSPORT AIRCRAFT TRAFFIC NEAR SEATTLE (Italicized values do not have minimum separation distance imposed.)

Comparison Level	Average Field			Peak Field			Peak/Average Field		
	Frequency < 1 GHz	Frequency > 1 GHz	All Frequencies	Frequency < 1 GHz	Frequency > 1 GHz	All Frequencies	Frequency < 1 GHz	Frequency >1 GHz	All Frequencies
DO-160B	3.1e-3 *1.4e-3*	2.6e-4 *1.8e-4*	3.4e-3 *4.7e-3*	2.3e-3 *3.4e-3*	2.1e-2 *2.0e-2*	2.3e-2 *2.3e-2*	5.4e-3 *7.8e-2*	2.1e-2 *217e-2*	2.6e-2 *2.8e-2*
DO-160C	0 *1.2e-5*	0 *0*	0 *1.2e-5*	0 *6.4e-6*	3.5e-5 *3.6e-4*	3.5e-5 *4.2e-4*	0 *1.9e-5*	3.5e-5 *3.6e-5*	3.5e-5 *4.2e-5*
Certification	0 *7.2e-5*	0 *0*	0 *7.2e-5*	0 *0*	0 *0*	0 *0*	0 *7.2e-5*	0 *0*	0 *7.2e-5*

TABLE 11. NUMBERS OF FLIGHTS WITH CALCULATED FIELD STRENGTH EXCEEDING COMPARISON LEVELS
(Italicized values do not have minimum separation distance imposed.)

	Denver Transport Aircraft (3168 total flights)			Seattle Transport Aircraft (1743 total flights)			Seattle Nontransport Aircraft (1003 total flights)		
Comparison Level	Frequency < 1 GHz	Frequency > 1 GHz	All Frequencies	Frequency < 1 GHz	Frequency > 1 GHz	All Frequencies	Frequency < 1 GHz	Frequency > 1 GHz	All Frequencies
DO-160B	517	3168	3168	389	1743	1743	407	1003	1003
	518	*3168*	*3168*	*403*	*1743*	*1743*	*395*	*1003*	*1003*
DO-160C	0	12	12	0	280	280	0	43	43
	0	*13*	*13*	*0*	*300*	*300*	*1*	*52*	*53*
Certification	0	0	0	0	0	0	0	0	0
	1	*1*	*2*	*0*	*0*	*0*	*4*	*0*	*4*

transport category value, or perhaps a little larger. If one uses 1.e-5 for the worst case upper limit probability of a HIRF-induced catastrophic aircraft event for the NPRM certification levels, then the reduction from probabilities associated with DO-160C and DO-160B are 3.5 and 2600, respectively.

ACCURACY AND RELIABILITY.

Limitations of effort, availability of reliable information, and existence of knowledge in some areas set the bounds on the accuracy and reliability of the results. The major elements contributing to uncertainty of the results are

- completeness and accuracy of the emitter and aircraft position information, including extrapolation to ground level,
- antenna gain and pattern approximations made in calculating the exterior field strengths at each aircraft position,
- approximations in frequency extrapolating the DO-160B/C bench tests standards and in converting them to exterior field values,
- worst case assumption about emitters being on and oriented so as to illuminate the aircraft, and
- the engineering judgments of the avionics properties and probabilities—P(avionics), P(frequency), P(level), and P(catastrophic).

It is hard to estimate the accuracy of the probability estimates, since there may be order of magnitude errors in some of the component probabilities. An informed guess is that, on average, the product of the avionics probabilities is probably good to an order of magnitude. The product of the probabilities for an emitter being on and oriented so as to illuminate an aircraft presently is a worst case upper limit and, depending on the HIRF level under consideration, could easily be 1-2 orders of magnitude smaller. The probability associated with emitter field strength at an aircraft exterior is probably good to a factor of two for HIRF strength levels at the DO-160C level or weaker. For relative probabilities between categories of aircraft, between Denver and Seattle and between different HIRF environments, accuracy up to a factor of two is a reasonable estimate when considering for field strengths less severe than the NPRM certification levels. Recall that probabilities obtained separately for Denver and Seattle varied by factors of 2-3.

In particular, consider that the upper limits derived for the NPRM certification levels for transport category aircraft depend upon only two flights with one emitter each (one of which is mobile). The calculated distance of closest approach of less than 110 ft in both cases is almost certainly underestimated due to the limited accuracy of the radar recording of the aircraft position. If the real separation distance were only 150 ft, neither flight would have experienced fields in excess of the certification level. For the nontransport category, of the six offending flights, four have a calculated elevation angle between emitter and aircraft that is negative at a distance of less than 200 ft. This is most likely due to an error in the recorded positions of either the aircraft and/or the emitters.

Likewise, the DO-160C associated results are dominated by one or two emitters in each category. If these emitters (e.g., a mobile AN/MPN14 in Denver and an AN/SPY-1 emitter in Seattle) are not actually in fulltime use or have significantly different operating characteristics than those used in this study, the corresponding probabilities could drop by one or two orders of magnitude.

The DO-160B associated probabilities, however, are much less likely to suffer from aircraft or emitter position errors or even from particular emitter characteristics. This is because these relatively low levels are exceeded for many emitters on each flight, a single aircraft position, or a single emitter.

REVIEW

A study has been completed to assess the risk of HIRF for transport and nontransport (fixed-wing) aircraft in the U.S. The approach to the assessment incorporated:

- detailed information on emitters and flights near two major cities
    - A total of 5913 flights of transport category aircraft involving a takeoff or landing in either the Denver or Seattle area were examined. A total of 893 emitters ranging in frequency from 500 kHz to 40 GHz were used, with some reasonable assumptions, to calculate electromagnetic field strengths at aircraft positions.
- quantitative judgments based on industry experience with aircraft and avionics
    - Dave Walen of the FAA and Richard Hess of Honeywell Flight Systems acted as resources with regard to the types of avionics on aircraft, their properties and the probabilities of different kinds of responses.
- HIRF environment levels from regulatory and standards sources
    - The probability of a catastrophic aircraft event was estimated for three different HIRF threat levels:

        1. DO-160B-derived field strengths
        2. DO-160C-derived field strengths
        3. NPRM certification field strengths

No reliable evidence was found to suggest that flights in the Denver and Seattle areas experience electromagnetic fields in excess of the NPRM certification levels. Worst case upper limits are estimated at ~2e-6 and ~1e-5 for transport and nontransport category aircraft, respectively. DO-160C associated HIRF catastrophic event probabilities are one to two orders of magnitude larger and DO-160B probabilities are three to four orders of magnitude larger than these pessimistic upper limits.

REFERENCES

1. FAA Notice of Proposed Rulemaking (NPRM) and JAA Notice of Proposed Amendment (NPA), "High-Intensity Radiated Fields (HIRF) Standards for Aircraft Electrical and Electronic System."

2. "Environmental Conditions and Test Procedures for Airborne Equipment," RTCA/DO-160B, Radio Technical Commission for Aeronautics, July 1984.

3. "Environmental Conditions and Test Procedures for Airborne Equipment," RTCA/DO-160C, Radio Technical Commission for Aeronautics, December 1989.

4. "High-Intensity Radiated Field External Environments for Civil Aircraft Operating in the United States of America," NAWCADPAX-98-156-TM, Naval Air Warfare Center, Aircraft Division, Patuxent River, MD, September 1998.

5. Elliott, James R. and Perala, Rodney A., "Statistical Study of the Closest Approach of Aircraft to Ground-Based Emitters," EMA-97-007, Electro Magnetic Applications, Inc., Denver, CO, March 1997.

6. Elliott, James R. and Perala, Rodney A., "Statistical Study of the Closest Approach of Aircraft to Ground-Based Emitters: Results for Seattle and Comparison With Denver," DOT/FAA/AR-99/5, April 1999.

7. Elliott, James R. and Perala, Rodney A., "Statistical Study of the Distance of Closest Approach of Aircraft to Ground-Based Emitters," DOT/FAA/AR-98/75, April 1999.